

# Quark Recombination and Heavy Quark Diffusion in Hot Nuclear Matter

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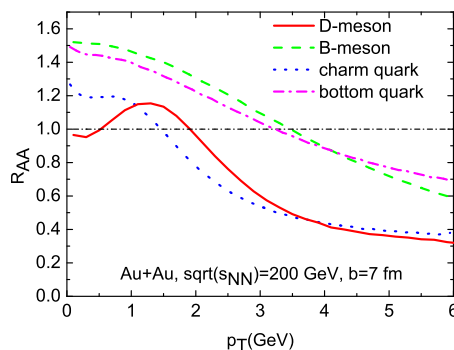
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**Abstract.** We discuss resonance recombination for quarks and show that it is compatible with quark and hadron distributions in local thermal equilibrium. We then calculate realistic heavy quark phase space distributions in heavy ion collisions using Langevin simulations with non-perturbative  $T$ -matrix interactions in hydrodynamic backgrounds. We hadronize the heavy quarks on the critical hypersurface given by hydrodynamics after constructing a criterion for the relative recombination and fragmentation contributions. We discuss the influence of recombination and flow on the resulting heavy meson and single electron  $R_{AA}$  and elliptic flow. We will also comment on the effect of diffusion of open heavy flavor mesons in the hadronic phase.

Quark recombination has been identified as an important mechanism of hadronization in high energy nuclear collisions [1, 2, 3, 4, 5]. Evidence for recombination can be seen in the large baryon/meson ratios and the quark-number scaling of elliptic flow  $v_2$  at the Relativistic Heavy Ion Collider (RHIC) [5]. First-generation recombination models that could explain these phenomena at intermediate transverse momenta  $p_T \approx 1.5 \dots 6$  GeV/ $c$  were based on so-called instantaneous quark coalescence. They lack explicit energy conservation and serious concerns arise if they are applied to low  $p_T$  where the bulk of hadrons are produced.

Hence it is important to understand how quark recombination in local kinetic equilibrium can be described. A promising formalism was put forward in [6, 7] based on a Boltzmann equation for quarks and antiquarks scattering through resonances which resemble mesons. This resonance recombination model (RRM) conserves 4-momentum and exhibits detailed balance. Therefore, in the long-time limit of the Boltzmann dynamics the mesons should acquire local thermal equilibrium with temperature and flow fields given by those of the equilibrated quark distributions. We have numerically confirmed this assertion both for simple blastwaves with constant hadronization time [8], and for the non-trivial hadronization hypersurface of a hydrodynamic evolution of the quark phase [9]. Hence resonance recombination preserves local thermal equilibrium for arbitrary flow fields and for any realistic hypersurface. An important corollary is the fact that any quark-number or kinetic energy scaling at *low* hadron- $p_T$  is not due to quark recombination. Local equilibration would not allow any microscopic information



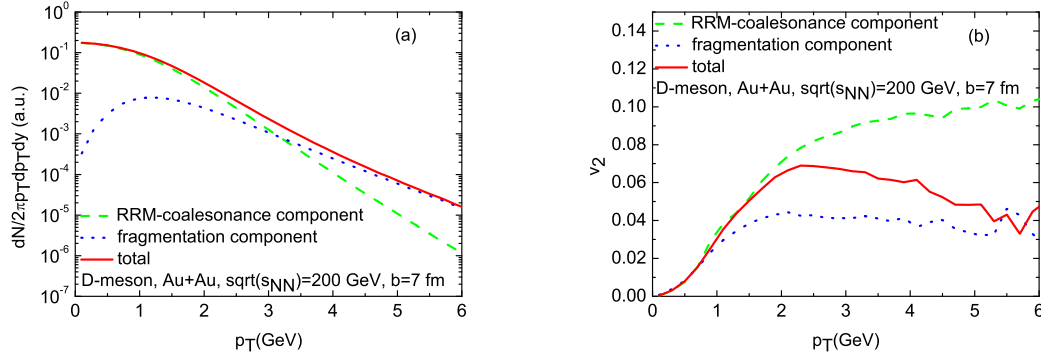
**Figure 1.**  $D$ - and  $B$ -meson nuclear modification factors for semi-central Au+Au collisions at RHIC compared to the  $c$  and  $b$  quark  $R_{AA}$  from which they originate.

about hadronization to be detected, and we explicitly show in Ref. [8] how a realistic flow field together with a reasonable freeze-out hierarchy for hadrons can mimic quark number- and kinetic energy scaling at RHIC at *low*  $p_T$  to good accuracy.

Heavy charm ( $c$ ) and bottom ( $b$ ) quarks have been widely discussed as ideal internal probes for quark gluon plasma, see [10] and references therein. The large masses increase their thermalization times, and the degree of thermalization in heavy ion collisions encodes valuable information about their interactions with quark gluon plasma (QGP). Here we report on our effort to set up a formalism that is consistently based on the notion of strongly coupled QGP, both for the diffusion of heavy quarks through QGP, and their hadronization through an appropriate superposition of recombination and fragmentation [9]. The latter provides an opportunity to extend the resonance recombination formalism to quark distributions away from local thermal equilibrium.

The dynamics of the heavy quarks in a background medium can be described by a relativistic implementation of the Langevin equation [11]. We use the ideal, 2+1-D, boost-invariant hydro code AZHYDRO [12, 13] to model the locally equilibrated background QGP medium. The drag and diffusion coefficients of the heavy quarks in the medium are calculated from non-perturbative  $T$ -matrix results on heavy-light quark interactions [14, 15]. The  $T$ -matrix approach exhibits Feshbach resonances both in the color-singlet and color-triplet channel and leads to resonant interactions up to  $\approx 1.5 T_c$ . The resonant relaxation rates are substantially enhanced compared to the corresponding perturbative elastic rates. The initial heavy quark momentum spectra are taken from perturbative calculations cross-checked with measured  $p+p$  semi-leptonic decay spectra [16], while the spatial distribution is determined by the binary collision density.

We employ a test particle method for our Langevin simulation. We have checked that in the limit of very large (unphysical) relaxation rates our charm quark distributions approach the equilibrium given by the hydrodynamic background. Figure 1 shows the nuclear modification factor  $R_{AA}$  for  $c$  and  $b$  quarks on the hadronization hypersurface (given by AZHYDRO) calculated from our Langevin with non-perturbative  $T$ -matrix coefficients for semi-central collisions at RHIC. We observe about 60% quenching for

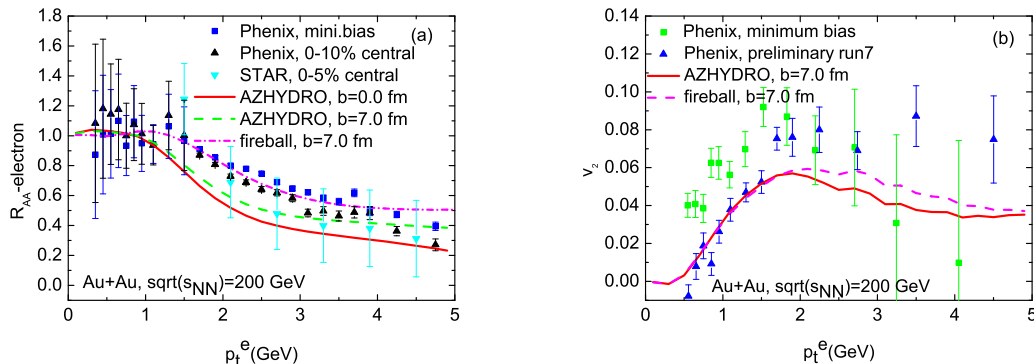


**Figure 2.** (a) The coalescence, fragmentation and total  $D$ -meson  $p_T$ -spectrum for semi-central Au+Au collisions at top RHIC energy. The total spectrum is normalized to one test-particle. (b): The same three contributions to the elliptic flow  $v_2$ .

charm quarks at large momenta  $p_t$  which is reflected in an excess at small  $p_t$  due to conservation of heavy quarks. Suppression for  $b$  is significantly smaller.

Hadronization of heavy quarks should proceed through coalescence with light quarks from the medium if heavy-light scattering rates are large enough to allow for such interactions in the color-singlet channel during the pertinent time interval (e.g. the duration of the mixed phase). On the other hand, if such heavy-light interactions are rare, e.g. at large  $p_t$ , independent fragmentation of the heavy quark should occur. For a given heavy quark momentum in its local fluid rest frame we estimate the scattering rate  $\Gamma_Q^{\text{res}}$  in the color singlet channel in the  $T$ -matrix approach at  $T_c$ . We approximate the coalescence probability through  $P_{\text{coal}}(p) = \Delta\tau_{\text{res}}\Gamma_Q^{\text{res}}$  (or  $P_{\text{coal}} = 1$  if the product exceeds one). In practice we boost the rates into the lab frame and apply them as a function of heavy quark  $p_t$  with  $\Delta\tau_{\text{res}} = 2 \text{ fm}/c$  (motivated by the fact that this time interval is well below the duration of the mixed phase in AZHYDRO) which leads to  $P_{\text{coal}} \rightarrow 1$  at vanishing  $p_t$ . Note that this approach treats the interactions of heavy quarks in the medium and their hadronization using the same non-perturbative dynamics. It also ensures that  $P_{\text{coal}} \rightarrow 0$  for very large  $p_t$ . We evaluate  $P_{\text{coal}}$  for each test particle and apply fragmentation or resonance recombination accordingly.

Figure 2 shows spectra and elliptic flow  $v_2$  for  $D$  mesons for semi-central collisions at RHIC. Fragmentation and recombination contributions are shown together with the total. Figure 1 provides  $R_{AA}$  for both  $D$  and  $B$  mesons. We notice that resonance recombination provides a significant enhancement of both radial and elliptic flow. The former can be seen from the prominent flow “bump” developing in  $R_{AA}$  for  $D$  mesons. Resonance recombination acts as an additional interaction of heavy quarks with the medium, making a noticeable contribution to further equilibration. In Figure 3 we display  $R_{AA}$  and  $v_2$  of electrons from semi-leptonic decays of  $D$  and  $B$  mesons, compared to experimental data. The comparison with data is favorable if one keeps in mind two facts: AZHYDRO is tuned to kinetic freeze-out and exhibits too little radial flow around  $T_c$ . This becomes obvious if the results with AZHYDRO are compared to those using



**Figure 3.** (a) Electron  $R_{AA}$  from semi-leptonic decays of  $D$  and  $B$  mesons for central ( $b = 0$  fm) and semi-central ( $b = 7$  fm) Au+Au collisions at RHIC. using either AZHYDRO or a parameterized fireball as the background medium. We compare to data from PHENIX [17] and STAR [18]. (b) Electron  $v_2$  from the same source.

a fireball parameterization with the correct radial flow at  $T_c$  (see [8, 9] for details). Secondly, we expect an increase in elliptic flow of about 20-30% in the hadronic phase. We have recently calculated relaxation rates of charm in a hadron gas and have found that at  $T_c$  the results tend to be close to those of the  $T$ -matrix calculation in QGP [19]. We will elaborate on both points further in a forthcoming publication.

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